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Discrimination surfaces with application to region-specific brain asymmetry analysis

Gabriel Martos^a and Miguel de Carvalho^{b*}

Discrimination surfaces are here introduced as a diagnostic tool for localizing brain regions where discrimination between diseased and non-diseased subjects is higher. To estimate discrimination surfaces, we introduce a Mann–Whitney type of statistic for random fields, and present large-sample results characterizing its asymptotic behavior. Simulation results demonstrate that our estimator accurately recovers the true surface and corresponding interval of maximal discrimination. The empirical analysis suggests that in the anterior region of the brain, schizophrenia patients tend to present lower local asymmetry scores in comparison to subjects in the control group. Copyright © 2017 John Wiley & Sons, Ltd.

Keywords: conditional area under the curve; distance to symmetry; Mann–Whitney statistic; neuroanatomical asymmetry; receiver operating characteristic; schizophrenia.

1. Introduction

The study of brain asymmetries is of fundamental importance to understand the origins of several diseases in humans and animals; see for instance [1], [2], [3], [4], and references therein. Morphological brain asymmetries have also been studied so to assess whether they contain information that can be used to discriminate between diseased and non-diseased subjects. For example, in a recent paper, [5] propose a Bayesian registration method for 3D MRI brain images and analyze brain-shape asymmetries by comparing schizophrenia with healthy (or control) subjects. To this aim, the authors propose a global measure of symmetry that consists in the ratio between the estimated left brain volume minus the estimated right brain volume, relative to the total volume of the brain, for each patient, and find weak evidence of differences between the two groups: schizophrenia vs. control patients. Neuroanatomical differences between schizophrenia patients and control patients have been widely discussed in other studies in the medical literature [e.g. 6, 3, 7, 8, 9]. Beyond differences at a morphological level, asymmetries of the brain at a functional level have also been examined [e.g. 10]. Neuroanatomical differences, between diseased and non-diseased subjects—rather than functional differences—will be the ones of interest in this article.

Despite the results by [5], the evidence for differences in morphological asymmetries between schizophrenia and control patients is not clear cut, and for instance in Narr et al. [11, p. 945] it can be read:

"Many studies have observed schizophrenia-related reductions (or reversals) in asymmetric perisylvian regions, but negative findings are common..."

With the exception of [5], most aforementioned studies are mainly descriptive and do not address from a rigorous statistical perspective where the location of structural differences between groups take place with higher probability.

In this article, we propose a novel statistical approach to localize specific regions on the brain where the asymmetry, measured as the difference between left and right sides in the brain, is more likely to be observed when comparing the group of schizophrenia patients with healthy controls subjects. To this aim, we propose what we refer to as a *discrimination*

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surface, and we use it to define two sets, namely: *intervals of maximal discrimination* (IMD) and *regions of over-threshold discrimination* (ROTD). Such surfaces and corresponding sets allow us to identify regions of the brain at which left-to-right morphological differences between diseased and non-diseased subjects are more likely to occur. From a conceptual viewpoint, discrimination surfaces—as formally defined in Section 3—have connections with the area under conditional ROC curves, as discussed for example by [12] and [13]. However, while in conditional ROC curves the objective is often on assessing how the discrimination ability of a diagnostic test changes over a predictor, here the goal is on searching for regions of maximum discrimination. Another object which has connections with discrimination surfaces is the so-called free-response ROC curve [14]; yet an important distinction between the two paradigms is that discrimination surfaces deliver as output a suspected location, whereas free-response ROC curve take as input suspected locations—along with a rating on the level of suspicion. Brain curves are modeled here as a functional data analysis [15, 16, 17] object, and are used to generate a random field of local asymmetry scores. To estimate discrimination surfaces we propose what we call as empirical discrimination surfaces, which can be regarded as a Mann–Whitney type of statistic for random fields, in the sense that such empirical surfaces consist of pointwise Mann–Whitney estimates. Some large-sample results characterizing the asymptotic behavior of our methods are derived, and in particular we show that under mild conditions the empirical surface is strongly uniformly consistent and that the corresponding IMD is weakly consistent. A smoothed version of the estimator is also discussed.

The article is organized as follows. In Section 2 we describe the data, from a schizophrenia study, that motivates the paper. In Section 3 we present the proposed discrimination surface-based methods. In Section 4 we assess the finite-sample performance of the proposed estimator in a simulation study. In Section 5 we analyze the data from the above-mentioned schizophrenia study. We conclude in Section 6. Proofs are included in the Appendix.

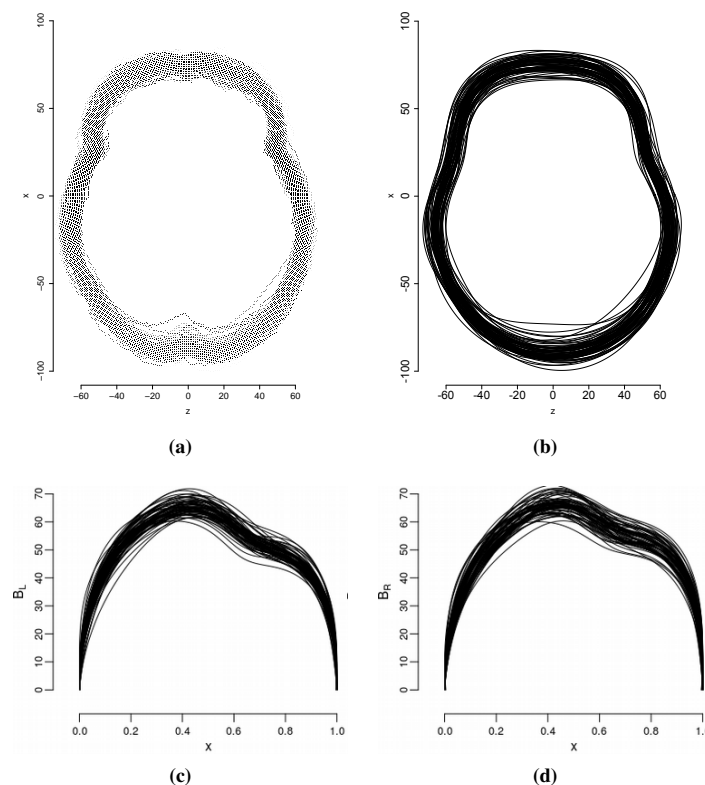


Figure 1. (a) Brain sections on the axial plane, for healthy and diseased subjects; x -axis: posterior \rightarrow anterior (back to front); z -axis: right \rightarrow left (“left” = patient’s left); and (b) Brain curves $\tilde{B} : [0, 2\pi] \rightarrow \mathbb{R}^2$. (c) Left $B_L : [0, 1] \rightarrow L \subset [0, \infty)$ and (d) Right $B_R : [0, 1] \rightarrow R \subset [0, \infty)$ brain curves after suitable rotations, reflections, and domain rescaling.

2. Description of study data

The raw data consists of $n = 68$ 3D MRI (Magnetic Resonance Images), gathered from a neuroscience study conducted at the University of British Columbia, Canada, and documented in [5]; the study involved $n_D = 30$ schizophrenia patients

and $n_{\bar{D}} = 38$ healthy controls. Some comments on the geometry of the data are in order. Following common practice in neuroscience, each brain was registered into the so-called Talairach space [18]—so that brains can be compared on the same three-dimensional referential coordinate space. The x -axis is created through the identification of two landmarks: the AC (anterior commissure) and the PC (posterior commissure), with the AC being the origin $(0, 0, 0)$; the remainder axes are the y -axis: inferior \rightarrow superior (bottom to top) and the z -axis: right \rightarrow left (“left” = patient’s left). Of main interest is the so-called axial plane, which corresponds to the x - z plane. In Figure 1 (a) we show the raw data corresponding to the x - z plane registered by the MRI scanner with $m = 500$ (x, z) coordinates on each subject; the other relevant perspectives, not shown here, are the sagittal plane (x - y) and the coronal plane (y - z). This data are in nature continuous, therefore the framework of functional data analysis [15, 16, 17] is natural to model brain sections on the axial plane. The raw data are available from the R package *shapes* [19].

Such data have been converted into functional data using a reproducing kernel Hilbert space approach discussed in the Supplementary Materials. After transforming the raw data into functions we obtain the brain curves $\tilde{B}_i : [0, 2\pi] \rightarrow \mathbb{R}^2$ for $i = 1, \dots, n$ shown in Figure 1 (b).

Following [5], we assume the midline plane of the brain as the line of symmetry, therefore we decompose the brain curves into left \tilde{B}_L and right \tilde{B}_R as follows:

$$\tilde{B}_L(\theta) = \begin{cases} \tilde{B}(\theta), & \text{if } \theta \in (\frac{\pi}{2}, \frac{3\pi}{2}], \\ 0, & \text{otherwise,} \end{cases}, \quad \tilde{B}_R(\theta) = \begin{cases} \tilde{B}(\theta), & \text{if } \theta \in (-\frac{\pi}{2}, \frac{\pi}{2}], \\ 0, & \text{otherwise.} \end{cases}$$

It is clear that $\tilde{B}(\theta) = \tilde{B}_L(\theta) + \tilde{B}_R(\theta)$ from the previous decomposition. To analyze the brain asymmetries with respect to the midline plane we rotate and reflect the functions \tilde{B}_L and \tilde{B}_R and also rescale the domain of both functions to the interval $[0, 1]$. In Figures 1 (c) and (d) we respectively represent left and right brain curves after these transformations; we denote these curves throughout as $B_L : [0, 1] \rightarrow L \subset [0, \infty)$ and $B_R : [0, 1] \rightarrow R \subset [0, \infty)$.

3. Discrimination surfaces

3.1. Distance to symmetry

Denote by D and \bar{D} the population of diseased and non-diseased subjects respectively, then for pairs of functional brain curves $(B_{L,D}, B_{R,D})$ and $(B_{L,\bar{D}}, B_{R,\bar{D}})$ we define the distance to local symmetry as follows:

$$Y_D(\mathbf{t}) = \int_a^b \{B_{L,D}(x) - B_{R,D}(x)\}^2 dx, \quad Y_{\bar{D}}(\mathbf{t}) = \int_a^b \{B_{L,\bar{D}}(x) - B_{R,\bar{D}}(x)\}^2 dx, \quad (1)$$

for $\mathbf{t} = (a, b) \in T$, where

$$T = \{(a, b) \in [0, 1]^2 : 0 \leq a < b \leq 1\}. \quad (2)$$

The scores in Equation (1) should be interpreted as measures of distance to symmetry in the region $[a, b]$, and for this reason we will refer to these as local asymmetry scores; indeed, for a completely symmetric brain, $B_L = B_R$, it holds that $Y(\mathbf{t}) = 0$, for all $\mathbf{t} \in T$. The larger the value of $Y(\mathbf{t}) = \int_a^b \{B_L(x) - B_R(x)\}^2 dx$, the less symmetric the brain should be on the region parametrized by \mathbf{t} . We refer to a and b as localization parameters.

3.2. Discrimination Surfaces, IMD, and ROTD

Using the local asymmetry scores $Y_D(\mathbf{t})$ and $Y_{\bar{D}}(\mathbf{t})$ from Equation (1) we define the *discrimination surface* as

$$\Lambda(\mathbf{t}) = P\{Y_D(\mathbf{t}) > Y_{\bar{D}}(\mathbf{t})\}, \quad \mathbf{t} \in T. \quad (3)$$

Such surfaces can be used for assessing discrimination between the local asymmetry scores of diseased and non-diseased subjects by appraising how likely it is for $Y_D(\mathbf{t})$ to be larger than $Y_{\bar{D}}(\mathbf{t})$, over the regions of the brain corresponding to the interval $(a, b) = \mathbf{t} \in T$. For the purpose of consistency with existing literature, the definition in Equation (3) follows the standard convention in medical diagnostic statistics—that a higher value of the ‘marker’ $Y_D(\mathbf{t})$ would be more indicative of disease—but all concepts in the paper can be readily adapted to the setting where a higher value of $Y_D(\mathbf{t})$ is less indicative of disease.

Another graphical device that can be used to summarize information on the discrimination ability over different intervals is the *discrimination contour*, which is defined as $\lambda_u = \{\mathbf{t} : \Lambda(\mathbf{t}) = u\}$, for $u \in (0, 1)$. We can interpret λ_u as the sets of intervals with the same discrimination power.

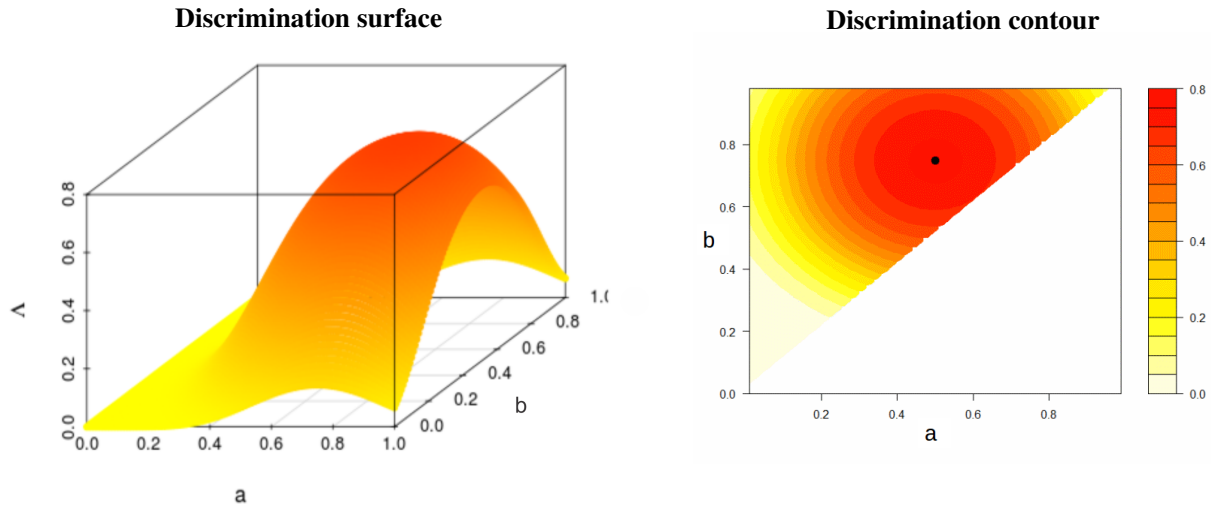


Figure 2. (Left) Bi-lognormal discrimination surface and corresponding discrimination contour (Right) using the configuration of parameters in Example 1. The solid black dot (•) represents the coordinates $t^* = (a^*, b^*) = (1/2, 3/4)$ underlying the interval of maximal discrimination, $\text{IMD} = [a^*, b^*]$.

Example 1 (Discrimination surfaces for lognormal distributed asymmetry scores). Consider the location and scale functions $\mu : [0, 1]^2 \rightarrow \mathbb{R}$ and $\sigma : [0, 1]^2 \rightarrow [0, \infty)$, with $\mu_D(t) > \mu_{\bar{D}}(t)$. Let $Y_D(t) \sim \text{LN}(\mu_D(t), \sigma_D^2(t))$ and $Y_{\bar{D}}(t) \sim \text{LN}(\mu_{\bar{D}}(t), \sigma_{\bar{D}}^2(t))$ be two independent and lognormal distributed asymmetry scores. Then,

$$\Lambda(t) = P\{Y_D(t) > Y_{\bar{D}}(t)\} = \Phi\left(\frac{\alpha(t)}{\{1 + \beta^2(t)\}^{1/2}}\right), \quad t \in T,$$

where Φ is the cumulative distribution function of the standard normal distribution, $\alpha(t) = \{\mu_D(t) - \mu_{\bar{D}}(t)\}/\sigma_{\bar{D}}(t)$ and $\beta^2(t) = \sigma_D(t)/\sigma_{\bar{D}}(t)$. The so-called bi-normal model is a particular case of the current model and it corresponds to the case $\mu_D(t) = \mu_D$, $\mu_{\bar{D}}(t) = \mu_{\bar{D}}$, $\sigma_D(t) = \sigma_D$, $\sigma_{\bar{D}}(t) = \sigma_{\bar{D}}$, with $\mu_D(t) > \mu_{\bar{D}}(t)$, and $\sigma_D, \sigma_{\bar{D}} > 0$; cf. Section 4.4 in [20]. In Figure 2 we plot an example of a bi-lognormal discrimination surface and corresponding discrimination contours with $\sigma_D(t) = \sigma_{\bar{D}}(t) = 1$, $\mu_{\bar{D}}(t) = 0$, and $\mu_D(t) = 1 - 10(b - 3/4)^2 - 10(a - 1/2)^2$, for $0 \leq a < b \leq 1$; note that in the latter specification, $\alpha(t) = \mu_D(t)$ and $\beta(t) = 1$.

In practice, one may also be interested in assessing on what regions discrimination is above a certain threshold and this leads us to define the *regions of over-threshold discrimination* (ROTD):

$$\text{ROTD}_u = \{t : \Lambda(t) \geq u \text{ or } 1 - \Lambda(t) \geq u\}, \quad u \in (0, 1). \quad (4)$$

Discrimination surfaces—as defined above—have connections with the area under conditional ROC curves [12, 13], defined as $\text{AUC}(x) = \int_0^1 \text{ROC}(p | x) dp$, where $\text{ROC}(p | x) = 1 - F_D(F_{\bar{D}}^{-1}(1 - p | x) | x)$, with x in \mathbb{R}^p being a covariate. Yet as it can be seen from Equation (4) (and as it will be seen from (5)), here the target is on seeking for regions of maximum discrimination, and not simply on assessing how discrimination ability changes over a covariate. Also, while in a typical conditional ROC curve setting, data are of the type $\{(X_{D,i}, Y_{D,i})\}_{i=1}^{n_D}$ and $\{(X_{\bar{D},j}, Y_{\bar{D},j})\}_{j=1}^{n_{\bar{D}}}$, in our context data consist of the random fields of asymmetry scores, that is

$$\{Y_{D,i}(t) : t \in T\}_{i=1}^{n_D}, \quad \{Y_{\bar{D},j}(t) : t \in T\}_{j=1}^{n_{\bar{D}}},$$

which we compute using $\{(B_{L,D,i}, B_{R,D,i})\}_{i=1}^{n_D}$ and $\{(B_{L,\bar{D},j}, B_{R,\bar{D},j})\}_{j=1}^{n_{\bar{D}}}$.

Since the goal is to localize brain regions where schizophrenia patients differ further from healthy controls. Then the regions of interest are those where one of the random variables is stochastically greater than the other with maximum probability. Therefore let $t^+ := \arg \max_{t \in T} \Lambda(t)$ and $t^- := \arg \max_{t \in T} 1 - \Lambda(t) = \arg \min_{t \in T} \Lambda(t)$, both well defined if we assume $\Lambda(t)$ is a uniformly continuous surface (note that T in Equation (2) is a compact set), then the region of interest is determined by $t^* := t^+$ if $\Lambda(t^+) > 1 - \Lambda(t^-)$ or $t^* := t^-$ otherwise. In this way we define the *interval of maximal discrimination* as

$$\text{IMD} = [a^*, b^*], \quad (5)$$

where the limits of this interval are defined through the elements in the vector $t^* = (a^*, b^*)$.

3.3. Estimating discrimination surfaces and their functionals

We start by noting that the trajectories of the random fields of asymmetry scores, as defined in Equation (1) live in \mathcal{Y} , the space of all non-negative and differentiable random functions on T such that $\partial Y(\mathbf{t})/\partial a \leq 0$ and $\partial Y(\mathbf{t})/\partial b \geq 0$, a.s. Indeed, it holds that

$$\begin{cases} \frac{\partial Y}{\partial a} = \frac{\partial}{\partial a} \left(\int_a^b \{B_L(x) - B_R(x)\}^2 dx \right) = -\{B_L(a) - B_R(a)\}^2 \leq 0, \\ \frac{\partial Y}{\partial b} = \frac{\partial}{\partial b} \left(\int_a^b \{B_L(x) - B_R(x)\}^2 dx \right) = \{B_L(b) - B_R(b)\}^2 \geq 0. \end{cases} \quad (6)$$

Keeping in mind the applied context under analysis—and to rule out uninteresting cases from a morphological perspective—we further assume that random functions in \mathcal{Y} are ‘bounded,’ in the sense that $P\{Y(\mathbf{t}) \in S\} = 1$, with $S = [0, M]$, for some possibly large but finite $M > 0$, for all $\mathbf{t} \in T$.

Let $F_{\mathbf{t}}(y) = P\{Y(\mathbf{t}) \leq y\}$, and define the marginal empirical distribution function as,

$$\hat{F}_{\mathbf{t}}(y) = \frac{1}{n} \sum_{i=1}^n I\{Y_i(\mathbf{t}) \leq y\}, \quad y \in S, \quad \mathbf{t} = (a, b) \in T,$$

where $I\{\cdot\}$ is the indicator function, and $Y_1(\mathbf{t}), \dots, Y_n(\mathbf{t})$ is a sequence of independent identically distributed random functions in \mathcal{Y} . Given that for each fixed \mathbf{t} , $F_{\mathbf{t}}(y)$ is a distribution function, the standard Glivenko–Cantelli theorem implies that, as $n \rightarrow \infty$, it holds that

$$\sup_y |\hat{F}_{\mathbf{t}}(y) - F_{\mathbf{t}}(y)| = o(1), \quad \text{a.s.} \quad (7)$$

Yet, since the trajectories of asymmetry scores live in \mathcal{Y} , a stronger result actually holds for our setting. Indeed, $F_{(\cdot, \cdot)}(y)$ is nondecreasing, and as a consequence of Equation (6) it follows that for $0 \leq a_0 \leq a_1 < b \leq 1$ then:

$$P\{Y(a_1, b) \leq y \mid Y(a_0, b) \leq y\} = 1 \quad \text{and} \quad P\{Y(a_0, b) \leq y \mid Y(a_1, b) \leq y\} \leq 1. \quad (8)$$

Therefore, by evaluating the ratio of the two conditional probabilities in Equation (8), we obtain that $P\{Y(a_0, b) \leq y\} \leq P\{Y(a_1, b) \leq y\}$, that is $F_{(a, \cdot)}(\cdot)$ is nondecreasing; the same reasoning can be used to verify that $F_{(\cdot, b)}(\cdot)$ is nonincreasing. The same monotonicity properties hold for the marginal empirical distribution function $\hat{F}_{\mathbf{t}}(y)$. Thus, monotonicity on each dimension of $F_{\mathbf{t}}(y)$ and $\hat{F}_{\mathbf{t}}(y)$, along with the extra assumption that the true $F_{\mathbf{t}}(y)$ is continuous, allows us to go beyond and state the following generalization of the result presented in Equation (7).

Theorem 1. *Let $Y_1(\mathbf{t}), \dots, Y_n(\mathbf{t})$ be a sequence of independent identically distributed random functions in \mathcal{Y} . Suppose $F_{\mathbf{t}}(y)$ is continuous for all (y, \mathbf{t}) in $S \times T$. Then, as $n \rightarrow \infty$, it holds that*

$$\sup_{(y, \mathbf{t})} |\hat{F}_{\mathbf{t}}(y) - F_{\mathbf{t}}(y)| = o(1), \quad \text{a.s.}$$

Given a random sample of size $n = n_D + n_{\bar{D}}$ of random fields of asymmetry scores from diseased and non-diseased subjects, define the *empirical discrimination surface* as

$$\hat{\Lambda}(\mathbf{t}) = \frac{1}{n_D n_{\bar{D}}} \sum_{i=1}^{n_D} \sum_{j=1}^{n_{\bar{D}}} I\{Y_{Di}(\mathbf{t}) > Y_{\bar{D}j}(\mathbf{t})\}. \quad (9)$$

Here, $Y_{Di}(\mathbf{t})$ is the distance to symmetry score, as defined in Equation (1), for the i th individual in the sample of diseased patients, and $Y_{\bar{D}j}(\mathbf{t})$ is the distance to symmetry score of the j th non-diseased subject in the control group.

Let $\hat{\mathbf{t}}^+ := \arg \max_{\mathbf{t} \in T} \hat{\Lambda}(\mathbf{t})$ and $\hat{\mathbf{t}}^- := \arg \max_{\mathbf{t} \in T} 1 - \hat{\Lambda}(\mathbf{t})$, then we define the estimated optimal localization vector parameter $\hat{\mathbf{t}}^* := \hat{\mathbf{t}}^+$ if $\hat{\Lambda}(\hat{\mathbf{t}}^+) > 1 - \hat{\Lambda}(\hat{\mathbf{t}}^-)$ and $\hat{\mathbf{t}}^* := \hat{\mathbf{t}}^-$ otherwise. The corresponding interval of maximum discrimination estimate consists of a random interval, $\widehat{\text{IMD}} = [\hat{a}^*, \hat{b}^*]$, where the limits of this random interval are defined through the elements in the vector $\hat{\mathbf{t}}^* = (\hat{a}^*, \hat{b}^*)$.

Empirical ROTD can be obtained by setting a high level of discrimination $u \in (0, 1)$, and consist of the following random subset of T ,

$$\widehat{\text{ROTD}}_u = \{\mathbf{t} : \hat{\Lambda}(\mathbf{t}) \geq u \text{ or } 1 - \hat{\Lambda}(\mathbf{t}) \geq u\}. \quad (10)$$

Some comments are in order. For each $\mathbf{t} \in T$, our estimator in Equation (9) is a Mann–Whitney type of statistic, and thus it is straightforward to show that it is pointwisely unbiased and pointwisely weakly consistent, i.e.

$$E\{\hat{\Lambda}(\mathbf{t})\} = \Lambda(\mathbf{t}), \quad \hat{\Lambda}(\mathbf{t}) - \Lambda(\mathbf{t}) = o_p(1), \quad (11)$$

assuming $n_D/n \rightarrow \rho_D \in (0, 1)$ and $n_{\bar{D}}/n \rightarrow \rho_{\bar{D}} \in (0, 1)$, with $\rho_D + \rho_{\bar{D}} = 1$. Beyond such straightforward statements, more can actually be said by taking advantage of our extended Glivenko–Cantelli theorem (Theorem 1 above).

In the theoretical considerations made below, we work under the following assumptions:

(A1) Suppose $Y_D(\mathbf{t})$ and $Y_{\bar{D}}(\mathbf{t})$ are in \mathcal{Y} , the space of all non-negative and differentiable random functions on T , such that $\partial Y(\mathbf{t})/\partial a \leq 0$ and $\partial Y(\mathbf{t})/\partial b \geq 0$, and which are supported over $S = [0, M]$, for some $M > 0$, for every $\mathbf{t} \in T = \{(a, b) \in [0, 1]^2 : 0 \leq a < b \leq 1\}$.

(A2) Suppose $F_{D\mathbf{t}}(y) = P\{Y_D(\mathbf{t}) \leq y\}$ and $F_{\bar{D}\mathbf{t}}(y) = P\{Y_{\bar{D}}(\mathbf{t}) \leq y\}$ are continuous in $T \times S$, and strictly increasing in $y \in S$.

(A3) Let $Y_{D,1}(\mathbf{t}), \dots, Y_{D,n_D}(\mathbf{t})$ and $Y_{\bar{D},1}(\mathbf{t}), \dots, Y_{\bar{D},n_{\bar{D}}}(\mathbf{t})$ be two independent sequences of independent identically distributed random functions in \mathcal{Y} .

(A4) Suppose that as $n \rightarrow \infty$, it holds that $n_D/n \rightarrow \rho_D \in (0, 1)$ and $n_{\bar{D}}/n \rightarrow \rho_{\bar{D}} \in (0, 1)$, with $\rho_D + \rho_{\bar{D}} = 1$.

Here, A1 and A2 are regularity conditions on the true data-generating process, whereas A3 and A4 are conditions about the way we sample from such process. For identification reasons, throughout we assume that $\Lambda(\mathbf{t})$ is uniquely maximized at \mathbf{t}^* ; this plays no role on the consistency of $\hat{\Lambda}(\mathbf{t})$. The following results hold.

Theorem 2. Suppose assumptions A1 to A4 hold. Let $\Lambda(\mathbf{t})$ be a discrimination surface, and $\hat{\Lambda}(\mathbf{t})$ be its empirical discrimination surface; let $\mathbf{t}^* = (a^*, b^*) \in T$ be the pair of points delimiting the interval of maximal discrimination, and $\hat{\mathbf{t}}^* \in T$ be their corresponding estimates. Then, as $n \rightarrow \infty$, it holds that:

1. $\sup_{\mathbf{t}} |\hat{\Lambda}(\mathbf{t}) - \Lambda(\mathbf{t})| = o(1)$, a.s.
2. $\hat{\mathbf{t}}^* - \mathbf{t}^* = o_p(1)$.

In addition to the empirical estimate of the discrimination surface, smooth estimations can be obtained by considering the following kernel-based version of our estimator in Equation (9),

$$\tilde{\Lambda}(\mathbf{t}) = \sum_{l=1}^L K_H(\mathbf{t} - \mathbf{t}') \hat{\Lambda}(\mathbf{t}'), \quad (12)$$

where L is the length of the grid over which we smooth the empirical discrimination surface, and H is a positive definite bandwidth matrix. In practice, both L and H act as smoothing parameters in the sense that if we increase L and fix H , we should expect to get smoother estimates.

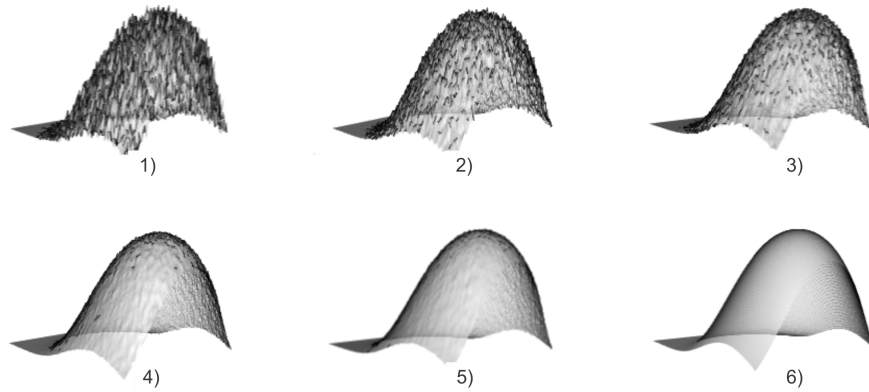
4. Simulation study

4.1. Preliminary experiments and preparations for Monte Carlo study

In this section we illustrate numerically the proposed methodology to estimate discrimination surfaces and corresponding IMD. To this aim, we use as a reference framework the bi-lognormal model introduced in Example 1. A Monte Carlo study will be reported in Section 4.2.

First, we simulate random samples of Y_D and $Y_{\bar{D}}$, the lognormal distributed asymmetry scores corresponding to the Example 1, with sample size: $n = 200, 1000, 2000, 10000$ and 20000 assuming that $\rho_D = \rho_{\bar{D}} = 0.5$. The estimated discrimination surfaces $\hat{\Lambda}(\mathbf{t})$ along with the corresponding discrimination contours $\hat{\Lambda}_u$ are presented in Figure 3. The results of this single-run experiment, suggest a fast convergence of the empirical discrimination surface, along with that of the corresponding interval of maximal discrimination. To evaluate the uncertainty around the estimation of the interval of maximal discrimination in this single-run experiment, we compute a bootstrap confidence region (CR) for the IMD. For that, we use the data relative to the sample size $n = 200$ and generate $B = 1000$ bootstrap samples from the original data. The bootstrap α -confidence regions, based on $\hat{P}(\text{IMD} \in \text{CR}_\alpha) = 1 - \alpha$ for $\alpha \in [0, 1]$, are reported in Figure 4, and for 95% confidence level, the estimated region contains the true localization parameter, $\mathbf{t}^+ = (a^+, b^+) = (1/2, 3/4)$. Coverage of the bootstrap will be assessed in the Monte Carlo study from Section 4.2.

Empirical discrimination surfaces



Empirical discrimination contours

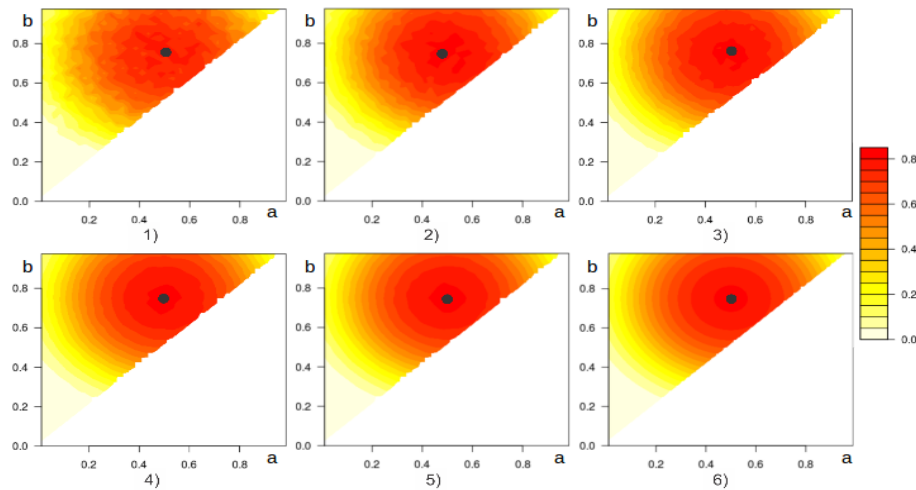


Figure 3. Above: Discrimination surface estimates $\hat{\Lambda}(t)$. Below: Corresponding discrimination contours. 1) $n = 200$, 2) $n = 1000$, 3) $n = 2000$, 4) $n = 10000$, 5) $n = 20000$, 6) True $\Lambda(t)$ and λ_c . In 6) the solid black dot (\bullet) represents the coordinates $t^+ = (a^+, b^+) = (1/2, 3/4)$ underlying the interval of maximal discrimination, $IMD = [a^+, b^+]$, whereas in 1–5) (\bullet) denotes its corresponding estimates.

4.2. Monte Carlo study

In this Monte Carlo study we investigate the performance of our estimator in Equation (9) over a variety of sample sizes and over two data configurations (Scenarios A and B). Specifically, we consider the following data generating processes based on the bi-(log)normal model from Example 1, where $\sigma_D(t) = \sigma_{\bar{D}}(t) = 1$ and

$$\mu_{\bar{D}}(t) = 0, \quad \mu_D(t) = 1 - 10(b - 3/4)^2 - 10(a - 1/2)^2, \quad 0 \leq a < b \leq 1, \quad (13)$$

Namely, we consider:

- Scenario A: $Y_D(t) \sim N(\mu_D(t), 1)$, with $\mu_D(t)$ as in (13), and $Y_{\bar{D}}(t) \sim N(0, 1)$, with $Y_D(t)$ independent of $Y_D(t')$ and $Y_{\bar{D}}(t)$ independent of $Y_{\bar{D}}(t')$, for $t \neq t'$.
- Scenario B: $Y_D(t)$ and $Y_{\bar{D}}(t)$ are Gaussian random fields with respective means $\mu_D(t)$ as in (13) and $\mu_{\bar{D}}(t) = 0$, and with Matérn covariance function, $\gamma(h) = \sigma^2 2^{1-\kappa} / \Gamma(\kappa) (h/\phi)^\kappa K_\kappa(h/\phi)$, for $h > 0$, where $\sigma = 1$, $\phi = 2$ and $\kappa = 0.5$ are the sill, range, and shape parameters, Γ is the gamma function, and with K_κ denoting the modified Bessel function of order κ .

Scenario A is thus the one we already used to produce the normal distributed asymmetry scores for the one-shot experiment in Section 4.1. We continue assuming $\rho_D = 0.5$ and consider again the sample size: $n = 200, 100, 2000, 10000$ and 20000 .

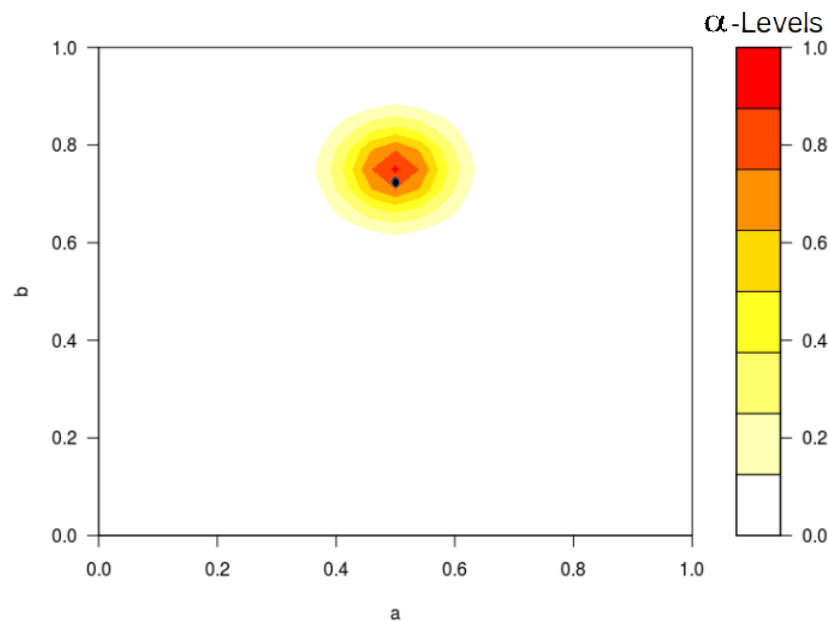


Figure 4. Bootstrap confidence regions along with true localization parameter $t^+ = (a^+, b^+) = (1/2, 3/4)$ (in a solid dot (•)) at different confidence levels .

For each sample size, we simulate $M = 1000$ datasets for each of the Scenarios A and B above. With each dataset we estimate the discrimination surface and the corresponding IMD; then we compute the mean integrated squared error (MISE) and mean squared error (MSE) as follows:

$$\text{MISE}_{\Lambda}^n = \frac{1}{M} \sum_{m=1}^M \int_T \{\hat{\Lambda}_m(t) - \Lambda(t)\}^2 dt, \quad \text{MSE}_{t^+}^n = \frac{1}{M} \sum_{m=1}^M \{(\hat{a}_m^+ - a^+)^2 + (\hat{b}_m^+ - b^+)^2\},$$

where $\hat{\Lambda}_m(t)$ is the estimate produced using the m th simulated dataset, with $\hat{t}_m^+ = (\hat{a}_m^+, \hat{b}_m^+)$ denoting its corresponding estimated localization parameters.

Table 1. Mean integrated squared error (MISE) estimates and mean squared error (MSE) (both on a scale of 10^3), respectively for Λ and t , over different sample sizes for Scenarios A and B as defined in Section 4.2. The standard-error is reported in parenthesis.

Scenario	Parameter	Sample size				
		200	1000	2000	10000	20000
A	Λ	3.833	0.765	0.380	0.076	0.038
		(0.230)	(0.047)	(0.024)	(0.005)	(0.002)
	t	5.766	2.761	2.014	0.963	0.739
		(5.320)	(2.482)	(1.787)	(0.874)	(0.680)
B	Λ	4.239	0.790	0.396	0.076	0.040
		(4.666)	(0.843)	(0.429)	(0.088)	(0.044)
	t	2.137	0.761	0.493	0.217	0.191
		(2.002)	(0.730)	(0.463)	(0.135)	(0.088)

Table 1 summarizes our Monte Carlo simulation study. As expected, MISE decreases as the sample size increases, both in terms of the MISE associated with $\hat{\Lambda}$ and \hat{t}^+ . However, it can be seen that in Scenario B the estimates of t^+ are more accurate for all sample sizes. This is due to the dependence structure introduced in the data generating process in Scenario B, that leads to a reduction of the variability associated to \hat{t}^+ . Note that MISE_{Λ}^n looks proportional to $1/n$, while $\text{MSE}_{t^+}^n$ seems to converge more slowly. This due to the fact the estimation of IMD is a challenging one, as the empirical discrimination surface is only smooth in the limit. We have also conducted some Monte Carlo experiments, with $n = 200$, so to assess coverage probability of the bootstrap confidence region for t^+ in Scenario A and B. The 99% and 95% coverage probabilities in Scenario A are 0.999 and 0.955, respectively. In Scenario B, the 99% and 95% coverage probabilities are 0.987 and 0.945 respectively. Thus, bootstrap confidence regions achieve nominal coverage in both scenarios.

5. Brain asymmetry analysis in schizophrenia patients

5.1. Context underlying the analysis

We now apply our methods to the brain curves from the study in Section 2. It has been suggested that schizophrenia patients may tend to have more symmetric brains than controls in the anterior and perisylvian regions [11, 21]. This result is controversial [3, 7, 8], and we show in this section that our methods can be used to localize brain regions where with maximum probability schizophrenic patients may differ further from healthy controls.

5.2. Discrimination surfaces and regions of maximal discrimination: Region-specific analysis

We estimate the empirical discrimination surface by using the asymmetry scores introduced in Equation (1). In Figure 5, we show the discrimination surfaces estimated using the methods proposed in Equations (9) and (12): At the top of the figure we show $\hat{\Lambda}(t)$ on the left and $\tilde{\Lambda}(t)$ on the right, and $1 - \hat{\Lambda}(t)$ and $1 - \tilde{\Lambda}(t)$ on the bottom (left and right respectively). The smoothed empirical discrimination surfaces corresponds to the smoothing parameters $L = 2775$ and $H = 0.1^3 I_{2 \times 2}$. Following Marron [22, p. 533], we conducted inference over a wide range of bandwidth matrices and grid sizes as a way to assess the sensitivity and reliability of the inference to the smoothing parameters L and H . The results do not differ substantially from the ones documented here for L and H close to the values selected to conduct the analysis.

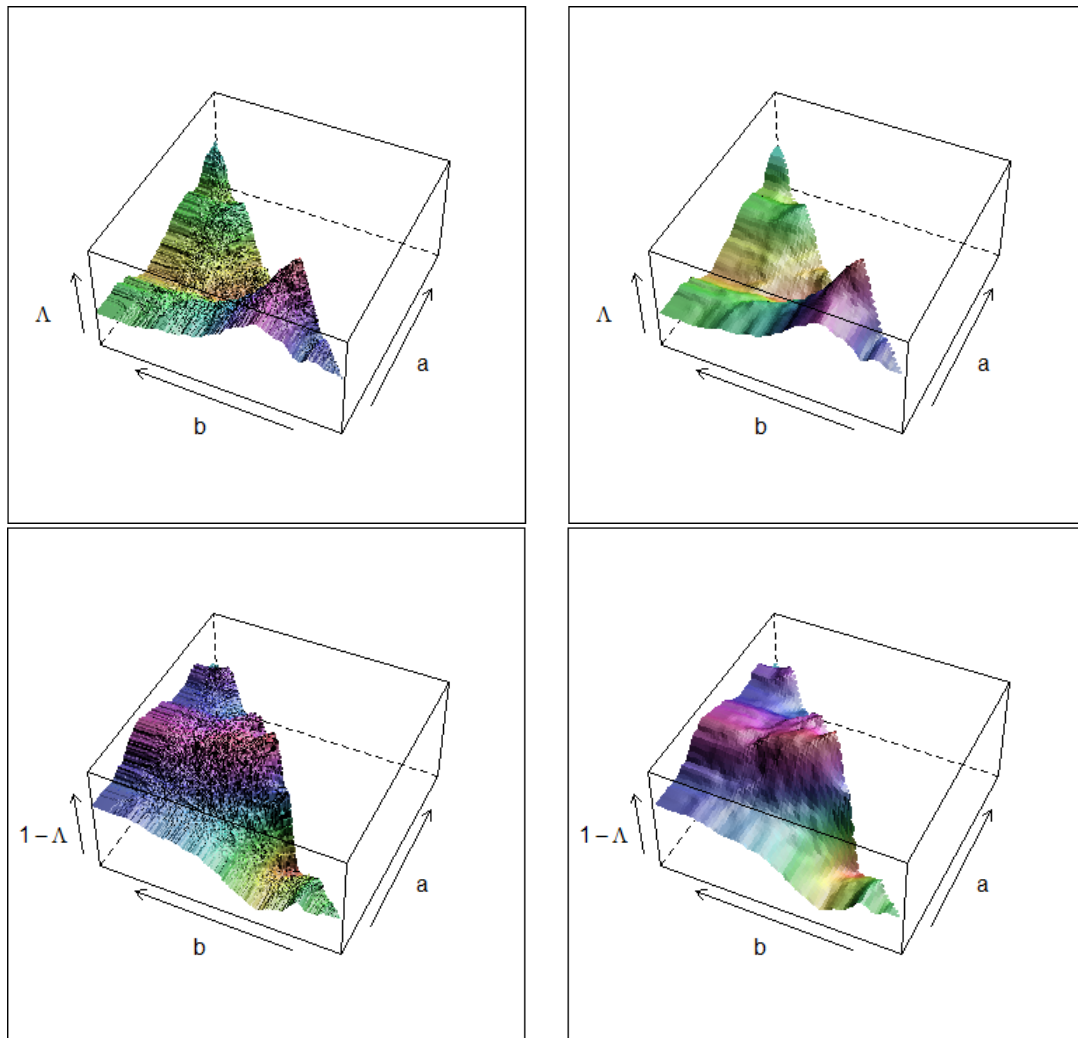


Figure 5. Discrimination surface estimates. Above: Empirical discrimination surface $\hat{\Lambda}(t)$ and its smoothed version $\tilde{\Lambda}(t)$. Below: reversed empirical discrimination surface $1 - \hat{\Lambda}(t)$ and its smoothed version $1 - \tilde{\Lambda}(t)$.

In most regions of the brain, as parametrized by t , one finds that $\hat{\Lambda}(t)$ is lower than $1 - \hat{\Lambda}(t)$; cf Figure 5; in particular $\max_{t \in T} \hat{\Lambda}(t) = \hat{\Lambda}(\hat{t}^+) \leq \max_{t \in T} 1 - \hat{\Lambda}(t) = \hat{\Lambda}(\hat{t}^-)$. Indeed, evidence provided by empirical discrimination

surfaces suggests that for the study data one is more likely to observe symmetric brains in the schizophrenia group of patients than in the healthy control group. Thus, we concentrate in $t^* = t^-$ as the estimation target in what follows.

We now turn our attention to the IMD as defined in (5). The corresponding estimate is $\widehat{\text{IMD}} = [0.44, 0.52]$ which corresponds partially to the perisylvian region of the brain. In the region parametrized by \hat{t}^* , the estimated probability $\hat{P}\{Y_D(\hat{t}^*) \leq Y_{\bar{D}}(\hat{t}^*)\} = 0.66$ can be interpreted as the estimated proportion of schizophrenic patients who present lower local asymmetry scores than a healthy patient in the region parametrized by \hat{t}^* . In Figure 6 we show the estimated average brain curves $(\bar{B}_{L,D}, \bar{B}_{R,D})$ and $(\bar{B}_{L,\bar{D}}, \bar{B}_{R,\bar{D}})$ and, highlighted in red, the region that corresponds to $\hat{t}^* = (0.44, 0.52)$. As can be seen, the “average-patient” in the control group have a more asymmetric brain than the “average-patient” in the disease group (notice that the area highlighted in red on the left-figure is greater that the same brain area on the right-figure) in the local region parametrized by \hat{t}^* .

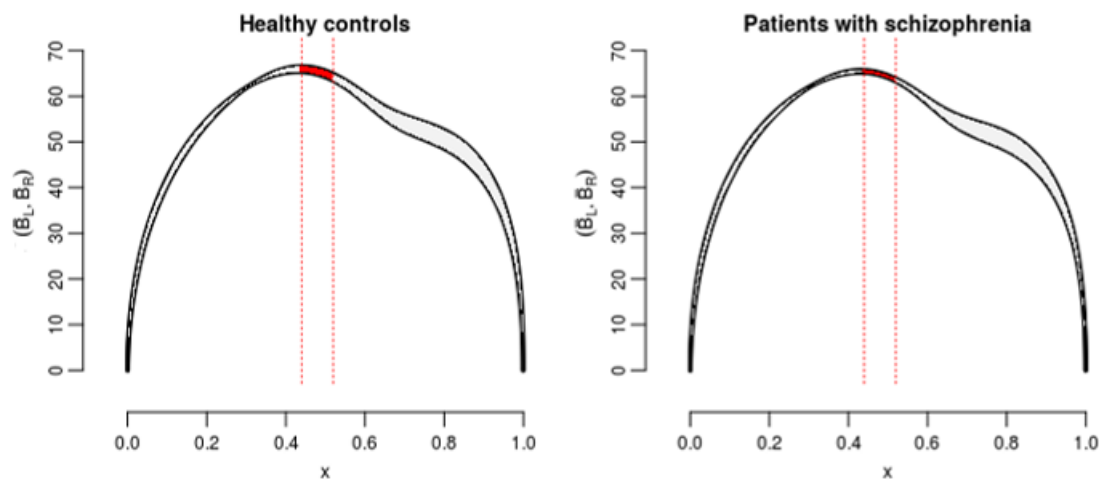


Figure 6. Average brain curves and the local region \hat{t}^* corresponding to estimated IMD (interval of maximal discrimination), as defined in Section 3.3, which corresponds to the point where the empirical discrimination surface attain its maximum.

The regions over-threshold discrimination, ROTD_u as defined in (4), was estimated using the plug-in estimator in (10); the result is presented in Figure 7 for $u = 0.60$ (on the left) and $u = 0.65$ (on the right). For the dataset we are considering here $\hat{\Lambda}(t) < 0.60$ for all $t \in T$, therefore the estimated ROTD_u only highlights regions where $\hat{P}\{Y_D(t) \leq Y_{\bar{D}}(t)\} \geq u$. In Figure 7 (left) we can see that schizophrenia patients present more symmetric brains than healthy patients in the regions of the brain corresponding to the anterior zone. Moreover, in Figure 7 (right), we observe that this difference in terms of symmetry is more likely to be observed in the perisylvian region of the brain, evidence which corroborated by the IMD estimate which localizes the region in Equation (10). Therefore, the empirical evidence obtained in this local-brain asymmetry study agrees with the results obtained by [11, 21]. A sensitivity analysis was conducted using other distances to local symmetry instead of Equation (1). The choice of the distance does not appear to affect our main findings; in particular, the IMDs corresponding to the L_1 and L_∞ distances to local asymmetry are $\widehat{\text{IMD}}_{L_1} = [0.45, 0.51]$ and $\widehat{\text{IMD}}_{L_\infty} = [0.47, 0.50]$. To assess the significance of the identified region of local asymmetry we used Hsieh and Turnbull [23, Th. 2.3], which implies that asymptotically $\sqrt{n_D}\{\hat{\Lambda}(t) - \Lambda(t)\} \sim N(0, \sigma^2) + o_p(1)$, with $\sigma^2 = 1/12(1/n_D + 1/n_{\bar{D}})$ —under the null $H_0 : \Lambda(t) = 1/2$. The null is rejected at the estimated IMD, and more importantly it is consistently rejected on a neighborhood of (\hat{a}, \hat{b}) . See Section 3 in the Supplementary Materials.

To describe the uncertainty around the IMD, we use the bootstrap to build a empirical confidence region for this parameter. The study was carried out using $B = 1000$ bootstrap samples from the original data. In Figure 8 we show the empirical α -confidence regions—computed from $\hat{P}\{\text{IMD} \in \text{CR}_\alpha\} = 1 - \alpha$ for $\alpha \in [0, 1]$ —that support the evidence of morphological differences in the brains between groups, being more likely to observe symmetric brains in the perisylvian and anterior regions in schizophrenia patients. In addition, in Figure 9 we show the bootstrap-based 95%-percentile functional confidence region for $P\{Y_D(t) \leq Y_{\bar{D}}(t)\}$ and $1 - P\{Y_D(t) \leq Y_{\bar{D}}(t)\}$. These empirical functional confidence regions can be used to assess the variance regarding the estimated discrimination surfaces and in particular the uncertainty around the estimated IMD.

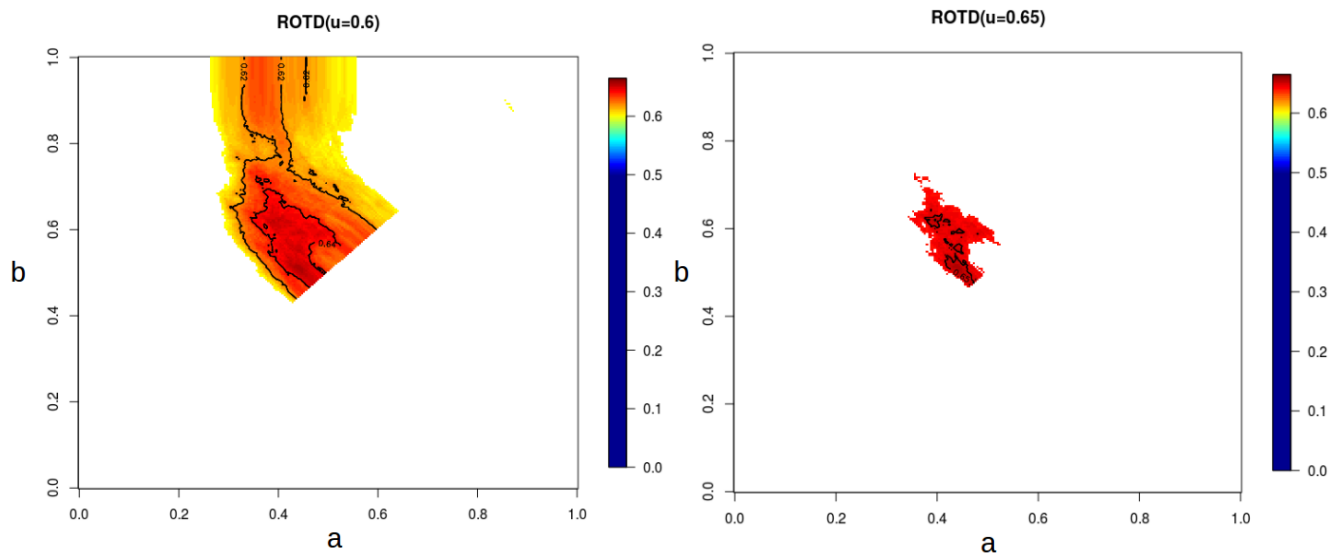


Figure 7. ROTD estimate (regions over-threshold discrimination) as defined in Equation (10) with $u = 0.60$ (left) and $u = 0.65$ (right), for brain asymmetry analysis data.

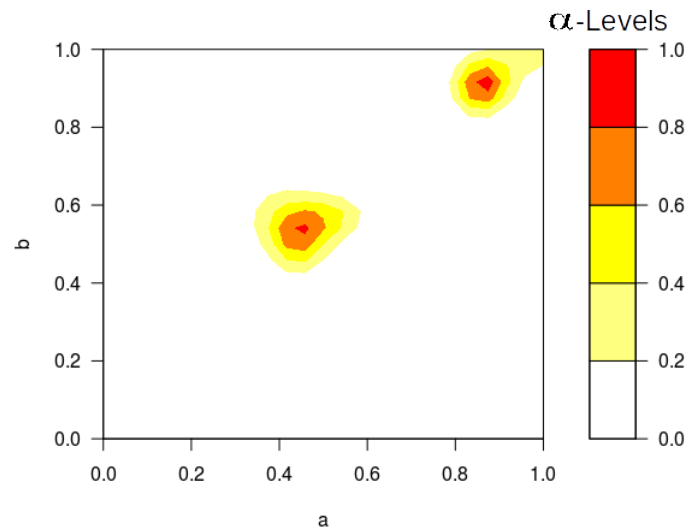


Figure 8. Bootstrap estimation of the CR for different confidence levels ($1 - \alpha$).

6. Discussion

Discrimination surfaces are here introduced as a diagnostic tool for localizing brain regions where discrimination between diseased and non-diseased subjects is higher. To estimate discrimination surfaces and associated regions of maximum discrimination, we introduce a Mann–Whitney type of statistic for random fields, and present large-sample results characterizing its asymptotic behavior. We have analyzed the data documented in [5] and found evidence of region-specific difference in terms of symmetry between the groups of healthy and schizophrenia patients. The empirical analysis suggests that for this study data, schizophrenic patients are more likely to present symmetric brains in the anterior region. In particular, with maximum probability, this difference in shape is observed in the perisylvian region as is also documented in [11, 21] and reference therein. An obvious limitation with empirical discrimination surface stems from the lack of ability to borrow strength across values of t , which motivates the need for also considering the smoothed version in (12).

A natural possibility for future work entails building alternative IMDs from other measures assessing discrimination between groups such as the Youden index [24]—which has links with the Kolmogorov–Smirnov statistic—or a standardized log-rank statistic [25, 26, 27]—which has links with the Wilcoxon rank statistic. Specifically, in a similar way that we argue here that discrimination surfaces have connections with the area under conditional ROC curves (cf Section 3.2), it would be natural modeling our applied setting of interest with an analogue of the covariate-adjusted Youden index [28], $YI_t = \max_{c_t} \{F_{\bar{D}t}(c_t) - F_{Dt}(c_t)\}$, with c_t being a function of t ; the corresponding IMD would in this case

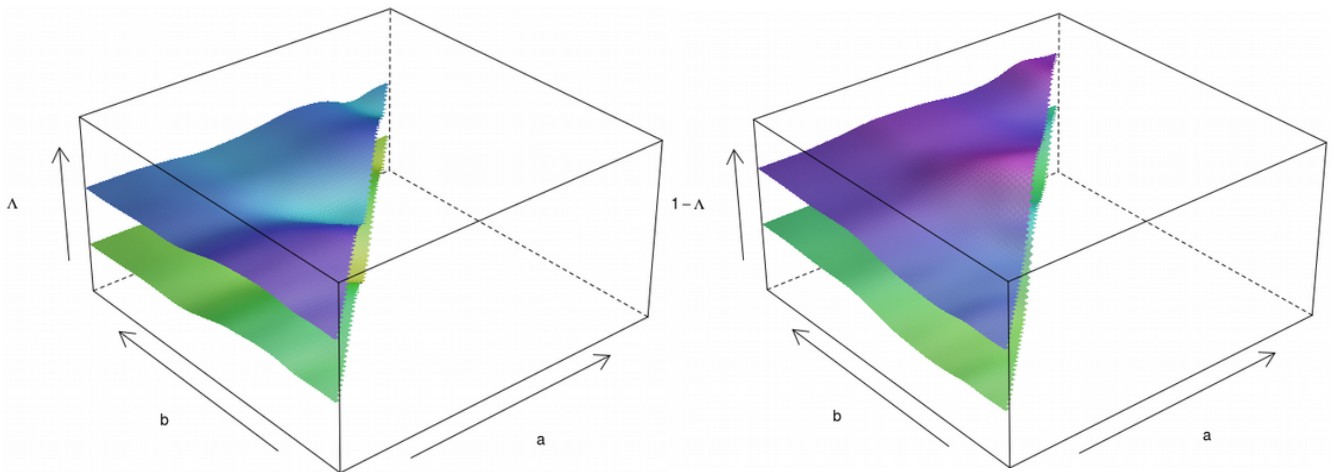


Figure 9. Empirical functional 95%-confidence interval for the discrimination surfaces: $\Lambda(t)$ on the left and $1 - \Lambda(t)$ on the right.

result from maximizing YI_t . In addition, a similar approach would entail developing standardized log-rank statistics for random fields, $|S_{c_t}|$, whose corresponding IMD would result from maximizing the discrimination surface $|S_{c_t}|$ over t in T .

Another natural avenue for future work is on extending the local-asymmetry analysis to 3D functional data so to estimate 3D regions of maximal discrimination. Accompanying the latest trends in the study of medical images [29, 30], a natural starting point for this would be to model the brain surface $\tilde{B}(x, y, z)$ as a Riemann manifold, \mathcal{M} , embedded in a normed vector space $(\mathbb{R}^3, \|\cdot\|)$. After a suitable partition and re-parametrization of the brain manifold into left and right brain sub-manifolds, $B_L(x, y, z)$ and $B_R(x, y, z)$, one could consider the set \mathcal{C} of closed smooth curves $\gamma: [0, 1] \rightarrow \mathcal{M}$, that is, for all $\gamma \in \mathcal{C}$ then $\gamma(0) = \gamma(1)$ and $\gamma'(0) = \gamma'(1)$; a curve belonging to this set determines a 3D closed region in the brain surface. Asymmetry scores in the local-region determined by the closed curve $\gamma \in \mathcal{C}$ could then be defined as

$$Y_D(\gamma) = \int_0^1 \{B_{L,D}(\gamma(s)) - B_{R,D}(\gamma(s))\}^2 ds, \quad Y_{\bar{D}}(\gamma) = \int_0^1 \{B_{L,\bar{D}}(\gamma(s)) - B_{R,\bar{D}}(\gamma(s))\}^2 ds,$$

along with the discrimination functional for such 3D setting,

$$\Lambda(\gamma) = P\{Y_D(\gamma) > Y_{\bar{D}}(\gamma)\}, \quad \gamma \in \mathcal{C}.$$

The variational problems associated to the local Region of Maximal Discrimination (RMD),

$$\gamma^+ =: \arg \max_{\gamma \in \mathcal{C}} \Lambda(\gamma) \quad \text{and} \quad \gamma^- =: \arg \max_{\gamma \in \mathcal{C}} 1 - \Lambda(\gamma),$$

would entail estimation over an infinite-dimensional parameter space \mathcal{C} , and thus would require the need of developing inference methods and asymptotics tailored for that setting.

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Appendix

In this appendix we use $F(y, a, b)$ to denote $F_t(y) = P\{Y(t) \leq y\}$ when the context so requires, and use the notation $F_{Dt}(y) = P\{Y_D(t) \leq y\}$ and $F_{\bar{D}t}(y) = P\{Y_{\bar{D}}(t) \leq y\}$, for $y \in S$ and $t \in T$. Also, $F_t^{-1}(p) = \inf\{y : F_t(y) \geq p\}$ are the marginal quantiles, $\hat{F}_t^{-1}(p) = \inf\{y : \hat{F}_t(y) \geq p\}$ are the marginal empirical quantiles, with $\hat{F}_t(y) = n^{-1} \sum_{i=1}^n I\{Y_i(t) \leq y\}$ denoting the marginal empirical distribution function.

A.1 Proof of Theorem 1

Our line of attack is similar to that of [31, p. 62]. Let $C_{i,j,k} = [y_i, y_{i+1}] \times [a_j, a_{j+1}] \times [b_k, b_{k+1}]$, with

$$0 = y_0 < y_1 < \dots < y_{I-1} < y_I = M, \quad 0 = a_0 < a_1 < \dots < a_{J-1} < a_J = 1, \quad 0 = b_0 < b_1 < \dots < b_{K-1} < b_K = 1,$$

be such

$$|F(y_{i+1}, a_{j+1}, b_k) - F(y_i, a_j, b_{k+1})| < \varepsilon,$$

for a given $\varepsilon > 0$, for $i = 0, \dots, I$, $j = 0, \dots, J$, and $k = 0, \dots, K$. By the monotonicity properties of $F_t(y)$ and $\hat{F}_t(y)$ on $S \times [0, 1]^2$ (namely: $F_{(\cdot, \cdot)}(y)$ and $F_{(a, \cdot)}(\cdot)$ are nondecreasing, $F_{(\cdot, b)}(\cdot)$ is nonincreasing, and analogous properties hold for $\hat{F}_t(y)$), it follows that

$$\begin{aligned} \Delta_n &\equiv \sup_{(y, t) \in S \times T} |\hat{F}_t(y) - F_t(y)| \leq \sup_{(y, t) \in S \times [0, 1]^2} |\hat{F}_t(y) - F_t(y)| \\ &= \max_{i, j, k} \sup_{(y, t) \in C_{i, j, k}} |\hat{F}_t(y) - F_t(y)| \\ &\leq \max_{i, j, k} \max\{|\hat{F}(y_{i+1}, a_{j+1}, b_k) - F(y_i, a_j, b_{k+1})|, |F(y_{i+1}, a_{j+1}, b_k) - \hat{F}(y_i, a_j, b_{k+1})|\}, \end{aligned}$$

and thus by taking the limit and using the strong law of large numbers,

$$\limsup_{n \rightarrow \infty} \Delta_n = \max_{i, j, k} \{ |F(y_{i+1}, a_{j+1}, b_k) - F(y_i, a_j, b_{k+1})| \} < \varepsilon, \quad \text{a.s.}$$

□

A.2 Auxiliary results

This appendix includes auxiliary lemmas which streamline the proof of Theorem 2 in Appendix A.3.

Lemma 1. Let $t \in T$, and let $g(t)$ be a function. Suppose that: i) $g(t)$ is uniquely maximized at t^* , ii) T is compact, iii) $g(t)$ is continuous, and iv) $\hat{g}(t)$ converges uniformly in probability to $g(t)$, and $\hat{t} = \arg \max_t \hat{g}(t)$. Then, as $n \rightarrow \infty$, it holds that

$$\hat{t} - t^* = o_p(1).$$

Proof. See Newey and McFadden [32, p. 2121].

□

Lemma 2. Let $Y_1(t), \dots, Y_n(t)$ be a sequence of independent identically distributed random functions in \mathcal{Y} . Suppose $F_t(y)$ is continuous for all (y, t) in $S \times T$ and strictly increasing for all y in S . Then, as $n \rightarrow \infty$, it holds that

$$\sup_{(p, t)} |\hat{F}_t^{-1}(p) - F_t^{-1}(p)| = o(1), \quad \text{a.s.}$$

Proof. The proof follows the same reasoning as that of Theorem 1 and can be found in the Supplementary Materials. □

Lemma 3. Suppose assumptions A1 to A4 of Section 3.2 hold. Then, as $n \rightarrow \infty$, it holds that

$$\sup_{(p, t)} |F_{Dt}\{\hat{F}_{Dt}^{-1}(p)\} - F_{Dt}\{F_{Dt}^{-1}(p)\}| = o(1), \quad \text{a.s.}$$

Proof. Since $F_{Dt}(y)$ is a bounded and continuous function for all (y, t) in $S \times T$, it is uniformly continuous and thus for every $\varepsilon > 0$ there exists a $\delta > 0$ such that

$$\sup_{(p, t) \in [0, 1] \times T} |\hat{F}_{Dt}^{-1}(p) - F_{Dt}^{-1}(p)| < \delta \Rightarrow \sup_{(p, t) \in [0, 1] \times T} |F_{Dt}\{\hat{F}_{Dt}^{-1}(p)\} - F_{Dt}\{F_{Dt}^{-1}(p)\}| < \varepsilon, \quad \text{a.s.} \quad (14)$$

Then, by the uniform convergence of $\hat{F}_{Dt}^{-1}(p)$ (Lemma 2), we can always find an $n > N(\varepsilon)$ such that the right-hand side of (14) holds, from where the final result follows. □

A.3 Proof of Theorem 2

Keeping in mind that the AUC coincides with the area under the ordinal dominance curve [23, p. 27], it follows that:

$$\begin{aligned} |\hat{\Lambda}(t) - \Lambda(t)| &= \left| \int_0^1 \hat{F}_{Dt}\{\hat{F}_{Dt}^{-1}(p)\} dp - \int_0^1 F_{Dt}\{F_{Dt}^{-1}(p)\} dp \right| \\ &\leq \int_0^1 |\hat{F}_{Dt}\{\hat{F}_{Dt}^{-1}(p)\} - F_{Dt}\{\hat{F}_{Dt}^{-1}(p)\}| dp + \int_0^1 |F_{Dt}\{\hat{F}_{Dt}^{-1}(p)\} - F_{Dt}\{F_{Dt}^{-1}(p)\}| dp \\ &\leq \sup_{p \in [0,1]} |\hat{F}_{Dt}\{\hat{F}_{Dt}^{-1}(p)\} - F_{Dt}\{\hat{F}_{Dt}^{-1}(p)\}| + \sup_{p \in [0,1]} |F_{Dt}\{\hat{F}_{Dt}^{-1}(p)\} - F_{Dt}\{F_{Dt}^{-1}(p)\}|, \end{aligned}$$

and thus

$$\sup_t |\hat{\Lambda}(t) - \Lambda(t)| \leq \sup_{(p,t) \in [0,1] \times T} |\hat{F}_{Dt}\{\hat{F}_{Dt}^{-1}(p)\} - F_{Dt}\{\hat{F}_{Dt}^{-1}(p)\}| + \sup_{(p,t) \in [0,1] \times T} |F_{Dt}\{\hat{F}_{Dt}^{-1}(p)\} - F_{Dt}\{F_{Dt}^{-1}(p)\}|.$$

Strong uniform consistency of $\hat{\Lambda}$ follows by observing that a.s. convergence to zero of the left-hand term follows by Theorem 1, whereas a.s. convergence to zero of the right-hand term follows by Lemma 3.

Weak consistency of \hat{t} then follows from Lemma 1 and by noting that $\Lambda(t)$ is continuous. To justify the latter claim note that by assumption $F_{Dt}\{F_{Dt}^{-1}(p)\}$ is a bounded and continuous function for (p, t) in $[0, 1] \times T$, and thus it is uniformly continuous, so that for every $\varepsilon > 0$ there exists a $\delta > 0$, such that if $\max\{|p - p'|, |a - a'|, |b - b'|\} < \delta$, then

$$|F_{Dt}\{F_{Dt}^{-1}(p)\} - F_{Dt'}\{F_{Dt'}^{-1}(p')\}| < \varepsilon. \quad (15)$$

Continuity of $\Lambda(t)$ then follows from (15) and the fact that to ensure $|\Lambda(t) - \Lambda(t')| < \varepsilon$, we only need to set $\delta > \max\{|a - a'|, |b - b'|\}$. □

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